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Methodology for Development of Customized Customer Damage Functions for Evaluation of Financial Losses due to Voltage Sags and Interruptions

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***Abstract*—The paper proposes new methodology for development of customized damage functions for evaluation of financial losses incurred by industrial users due to voltage sags and short interruptions. The existing customer damage functions (CDF), developed based on past surveys, are suitably scaled and transformed into comparable platform using financial conversions. The modified CDFs are then compared with the target user performance and combined into a new damage function unique to the target user. The paper provides detailed step-by-step procedure for implementation of the methodology in order to facilitate its practical use.**

***Index Terms*—customer damage function, financial losses, power quality, reliability, voltage sag**

I. Introduction

GLOBAL evaluation (network or country based) of financial losses of industrial plants due to voltage sags and interruptions has been a subject of intense interest during the past decade. Over the years, researchers have developed many ways (i.e. deterministic, probabilistic and fuzzy logic) to tackle the problem [1-7]. The underlying issue faced in these evaluations, regardless of the method used, is the lack of a single most important value for realistic representation: the nominal loss value for a process interruption. The nominal loss value of an industrial process, also referred to as the "maximum loss value" [7], is the financial loss incurred due to process interruption during peak production period. This parameter is typically used as the basis for calculation of financial losses due to voltage sags and interruptions and it also often serves as the "typical" value of loss incurred by process interruption. This obviously in many instances may lead to gross overestimation of total losses.

In conventional financial loss evaluation studies, the nominal loss value is usually obtained from customer damage functions (CDFs) derived from survey results. These CDFs provide general indication of expected value financial loss. However, a "one size fits all" approach is not good enough when accurate assessment is crucial. There are huge differences reported in nominal financial loss values depending on the type of industry, size of industrial plant and the region of the world were survey was carried out. It is impossible to find a single survey result that would fit perfectly the requirements of a particular case study (unless the survey was actually done in the plant of interest). Ideally, evaluations of expected loss should therefore be based on multiple sources from as many survey results as possible.

To achieve this, a robust methodology is required that is capable of analyzing and combining past survey results from different regions of the world and of different time frames, and generating a customized CDF for the plant of interest. This paper proposes one such methodology. It evaluates past survey results by comparing the characteristics of the assessed plant with the characteristics of the survey samples. The characteristics of interest include the type of industrial activity involved, the size of the assessed customer in terms of peak power demand (in kW) and the geographic location of the assessed plant. Once scaled and analyzed the characteristics of the past surveys are suitably merged to produce a new customized customer damage function (CCDF) for the customer/industry in question. The CCDF therefore represents a marked improvement compared to previous approaches and ensures more realistic assessment of financial losses incurred by process failure.

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II. Data Preparation

The proposed methodology requires the input data in a particular format. The conversion of raw data into useable, formatted information involves procedures aimed at ensuring that the information from various sources are comparable.

A. Gathering Raw Data

TABLE I shows the input data required by the method. For the customer under assessment, information describing its business type, operation size and location is needed, as those are the main characteristics dictating the magnitude of customer financial loss [8, 9].

Business type is defined by the NACE system, i.e., European standard for industry classification. The customer's

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peak demand determines its size, whereas the location of the customer depends on the country where its operations are based.

TABLE I
REQUIRED DATA FROM THE SURVEY AND THE ASSESSED PLANT

Customer under Assessment	Information of Surveys
NACE code, peak kW demand, location	Damage function for the industrial sector involved, NACE codes covered by the damage function, survey size, year of survey, average customer size, location/country performed, currency used

The same set of information needs to be extracted from the survey results, with additional data as shown in TABLE I.

TABLE II
PLANT UNDER ASSESSMENT

Parameter	Value
NACE code	22.1.0 (Manufacture of rubber products)
Peak kW	15000
Location	Thailand

TABLE III
SURVEY INFORMATION

Survey	**1** [10]	**2** [10]	**3** [11]	**4** [12]	**5** [13]
NACE of sample	20, 22.1	20, 22.1	19, 20, 22	20	22.2
Four digit NACE (modified)	20.0.0 22.1.0	20.0.0 22.1.0	19.0.0 20.0.0 22.0.0	20.0.0	22.2.0
Survey size	23	65	127	No data	No data
Year conducted	2000	2000	2006	2001	1996
Location	Thailand A	Thailand B	South Korea	Greece	Nepal
Average customer size (kW peak)	No data	No data	12617	No data	No data
Own Currency	Thai Baht	Thai Baht	Korean Won	Euro	Nepalese Rupee (Rs)
Currency Presented	Thai Baht	Thai Baht	US Dollar	US Dollar	Nepalese Rupee

To illustrate the method, the process of obtaining CCDF for an arbitrary industrial plant is demonstrated. The relevant plant information is given in TABLE II. Five different surveys are used in this example, with information shown in TABLE III. Fig.1 shows a typical customer damage function given in [13].

B. Modifying the Raw Data

The CDFs resulted from different surveys are usually given in different formats. The differences in data such as the business types involved, the currency in which the costs are expressed , and the year of survey have to be suitably modified prior to further evaluations. There are four steps involved in modifying original CDFs : currency conversion, discounting and compounding, conversion to a common currency, and extrapolation.

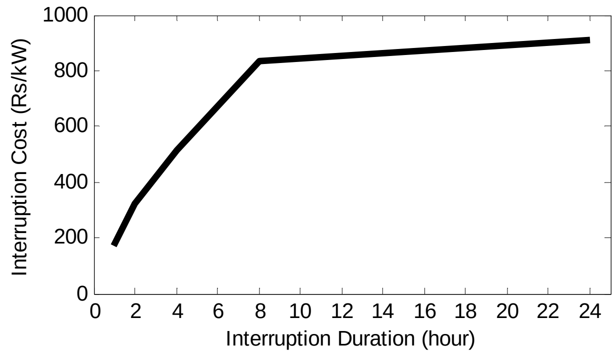

Fig. 1. CDF from survey 5

Currency conversion

This methodology requires the use of the countries' own currency in evaluation. Therefore, all surveys with results presented in a foreign currency should have the cost values in the damage function converted back into their country's own currency. This must be done with the exchange rate used in the survey itself, at the time the survey was done.

Discounting and Compounding

Money has a time value. The same amount today was worth less a year ago, and will be worth more a year later. The former statement is the discounting effect and is described by (1), whereas the later is the compounding effect described by (2). *PV* and *FV* are present and future values, *r* is the discount/compound rate and *n* is the number of years ago/ahead.

$$PV = \frac{FV}{\left(1+r\right)^n} \quad (1)$$

$$FV = PV \cdot \left(1+r\right)^n \quad (2)$$

For example, with *r* of 5% (*r*=0.05), using (1), 100 Euros today were only worth 95.2 Euros a year ago. With (2), 100 Euros today will be worth 105 Euros next year. This effect has to be incorporated in the methodology to conserve accuracy.

Using actual inflation rate based on consumer price index as the discount rate, for the countries where survey is conducted, the monetary values in the CDFs are converted into year 2005 values. For example, Survey 5 (TABLE III) is conducted in 1996 in Nepal. The inflation rates over the years are given in Table IV. Because we are calculating future worth, (2) is used as follow:

$$FV_{2005} = PV_{1996} \cdot (1.081) \cdot (1.07) \cdot (1.067) \cdot (1.114) \cdot (1.034) \ldots$$
$$\cdot (1.024) \cdot (1.029) \cdot (1.048) \cdot (1.04) = 1.633 PV_{1996}$$

The modified (treated) CDF is given in Fig. 2. It can be seen that it has much higher values compared to the original CDF.

TABLE IV
INFLATION RATE BASED ON CONSUMER PRICE)

Year	Thailand	South Korea	Greece	Nepal
1996	5.87	4.93	7.87	8.10
1997	5.58	4.49	5.44	7.00
1998	8.08	7.51	4.52	6.70
1999	0.31	0.81	2.14	11.40
2000	1.55	2.26	2.89	3.40
2001	1.66	4.07	3.65	2.40
2002	0.64	2.76	3.92	2.90
2003	1.80	3.52	3.44	4.80
2004	2.77	3.59	3.02	4.00
2005	4.54	2.75	3.49	4.50
2006	4.64	2.24	3.31	8.00
2007	2.23	2.54	2.99	6.40
2008	3.52	3.40	3.50	6.40

Source: International Monetary Fund (IMF)

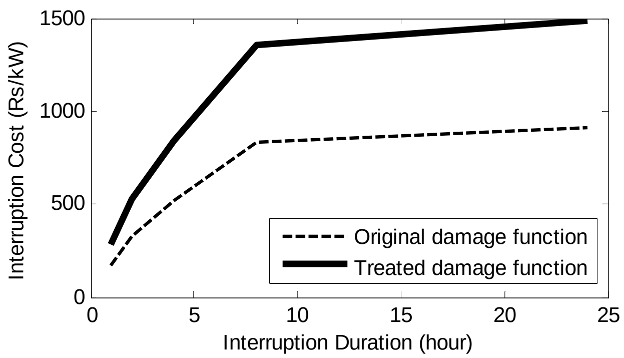

Fig. 2. The original and treated CDF

Conversion to Common Currency

The next step is to convert all currency values into a common currency. Instead of using market exchange rate as conversion rate, the purchasing power parity (PPP) exchange rate is used. Unlike market rate, "Purchasing Power Parities (PPPs) are currency conversion rates that both convert to a common currency and equalise the purchasing power of different currencies"[14]. PPP represents the "real" conversion rate where the difference in price level is eliminated during conversion [14]. In other words, it represents the actual value of money in different surveyed countries.

The US Dollar is chosen as the platform due to ease of data acquisition. The most recent data that covered all surveyed countries are from [15], which reported PPP exchange rate of year 2005. TABLE V shows the conversion rates of the related currencies. Dividing the monetary values in CDFs developed in different countries with the given exchange rates will yield results in common US Dollar values, as shown in Fig. 3.

TABLE V
PURCHASING POWER PARITY EXCHANGE RATE

Currency	Equivalent to 1 US Dollar
Thai Baht	15.93
Korean Won	788.92
Euro	0.70
Nepalese Rupee	22.65

Extrapolation

Due to the fact that the duration ranges covered by the surveys are not the same, extrapolation techniques need to be applied to some of the functions (Survey 1 and Survey 2). The most straightforward method is linear extrapolation. Fig. 4 shows the CDFs after extrapolation.

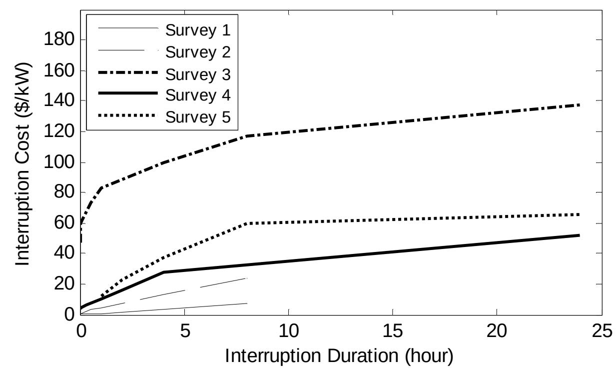

Fig. 3. CDFs from different surveys expressed in US Dollars

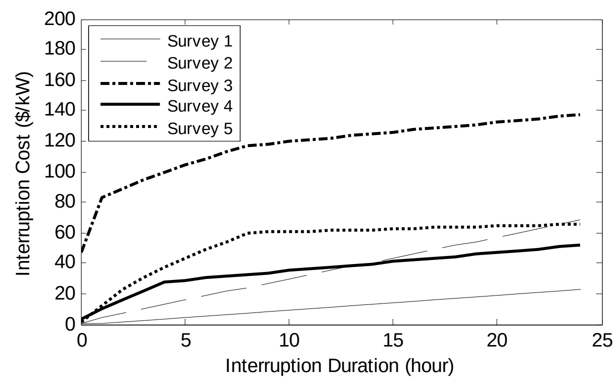

Fig. 4. CDFs after linear extrapolation

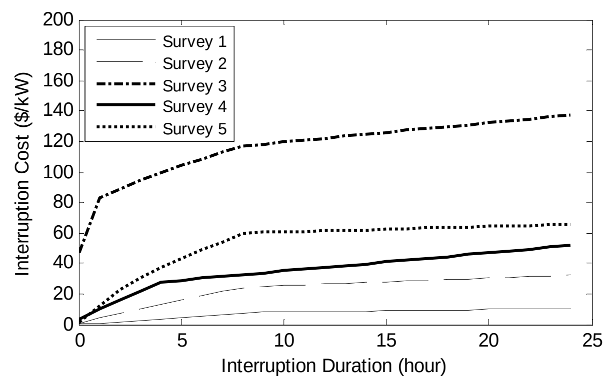

Fig. 5. CDFs after extrapolation considering the variable gradient

However, as the CDFs from all other surveys show a decrease in gradient with duration, taking into account this change in gradient is a more realistic alternative. By calculating the gradient of the last two sections of the functions, it is found that Survey 3 function has a 71% decrease in gradient, whereas the decrease in gradient of CDFS of Survey 4 and Survey 5 are 79.8% and 93.7% respectively. Taking an average of the three, CDFs of Survey 1 and 2 should have an 81.5% decrease in gradient in the final section of the curve. Based on this assumption, extrapolation is performed on Survey 1 and Survey 2 damage functions, resulting in a complete duration range as shown in Fig.5.

III. Matching Index

A *Matching Index* is calculated for all surveys considered. It defines the level of similarity of the assessed plant with the plants assessed in surveys. In other words, it measures how well the assessed plant can be represented by the surveys. Calculation involves comparing characteristics of the assessed plant (TABLE II) with the information provided by considered surveys (TABLE III).

A. Missing Data

To obtain realistic and accurate results, a complete set of data is necessary as input parameters. However, cases of incomplete data are quite usual. In the example used, some information regarding survey size and average customer size is missing (refer to TABLE III).

Proper treatment of the missing data is essential for this assessment. The proposed treatment methods are:

1) Penalty – This treatment puts a penalty on the surveys where non-complete information is provided. A very low score (i.e. zero) is assigned to the sectors where information is missing. Hence reducing the influence of the surveys with missing data.
2) Averaging – A score is obtained using the average value in the sector, derived from all other surveys used in assessment. This method preserves the influence of the survey with missing data.

B. Type Score

A survey can be used to represent the assessed plant if there are plants of the same industry type involved in the survey. Industry is identified using NACE codes. NACE is the European classification method of economic activities. It is a level-by-level basis classification where each industry is assigned a unique six digit code. The proposed methodology uses the first four digits of the NACE to obtain a *Type Score* for the surveys according to their similarity to the assessed plant.

By comparing NACE codes of the surveys and the assessed plant, a score can be obtained. *Type Scores* are assigned based on the following rules:

1) Maximum score is 1.0.
2) A score of 0 if the first two digits do not match
3) A score of 0.5 if the first two digits match.
4) A score of 0.8 if the first three digits match.
5) A score of 1.0 if all four digits match.
6) Total score divided by the number of codes (sectors) covered by the particular survey.

For example, based on the four digit NACE from TABLE III, Survey 1 will score 1.0 as one of its NACE code matches exactly that of the assessed plant. However, this score has to be divided by two as Survey 1 covered two NACE codes. The *Type Score* for all the surveys are given in TABLE VI.

C. Size Score

The magnitude of financial damage caused by power interruption is very much related to the size of the plant. Large plants loss more production and employee hours during interruptions compared to smaller plants. Therefore, it will not be realistic to represent a certain process with a survey that is based on very different sized samples.

The *Size Score* used in this methodology measures the closeness of the survey samples with the assessed plant. Scores are assigned by comparing the peak demand of the assessed plant with the average peak demand of the survey samples, based on the following rules:

1) Maximum score is 1.0.
2) A score of 1.0 for 10% or less difference in peak kW.
3) A score of 0.8 for 10% to 20% difference in peak kW.
4) A score of 0.6 for 20% to 30% difference in peak kW.
5) A score of 0.4 for 30% to 40% difference in peak kW.
6) A score of 0.2 for 40% to 50% difference in peak kW.
7) A score of 0 for more than 50% difference in peak kW.

These rules generated a score for each survey as shown in TABLE VI. The missing data in TABLE VI are treated using the averaging method described in the previous section.

D. Location Score

The location of a plant has significant influence on its CDF due to power interruptions. This is mainly caused by the difference in material, labour and operation costs in different countries. The effect of plant location is considered using *Location Scores*, where a score of 1.0 is assigned to surveys within the same country of the assessed plant, and a score of 0 if the survey is done outside the country of the assessed plant. The *Location Scores* of the surveys are given in TABLE VI.

TABLE VI
Type, Size and Location Scores

Survey	1	2	3	4	5
Type Score	0.50	0.50	0.17	0	0.50
Size Score	0.80	0.80	0.80	0.80	0.80
Location Score	1.0	1.0	0	0	0

E. Relative Strength

A parameter called *Relative Strength* is introduced to define the “confidence” of a particular survey as a reference. This parameter is based on the number of plants participating in the survey (survey size in TABLE III). Logically, the higher the sample size, the higher the “confidence”. *Relative Strength* describes this “confidence” as a comparison among all surveys involved in the evaluation. It is defined by (3) where the survey with the smallest survey size has a *Relative Strength* of 1.0 and all other surveys have *Relative Strength* larger than 1.0.

In (3), *RS* is the *Relative Strength* of survey n, while s is the sample size. *RS* for each of the five surveys of TABLE III is given in TABLE VII

$$RS_n = 1 + \log_{10}\left(\frac{s_n}{s_{\min}}\right) \quad (3)$$

TABLE VII
RELATIVE STRENGTH OF THE SURVEYS

Survey	1	2	3	4	5
Relative Strength	1.0	1.45	1.74	1.50	1.50

F. Calculation of Matching Index

Based on *Type Score*, *Location Score* and *Size Score*, factoring in the *Relative Strength* of the surveys, a set of *Matching Indices* is generated using (4).

$$MI_n = TS_n\left(1 + a\cdot SS_n + b\cdot LS_n\right)\cdot RS_n \quad (4)$$

For survey *n*, *MI* is the Matching Index, *TS* is *Type Score*, *SS* is *Size Score*, *LS* is *Location Score*, and *RS* is *Relative Strength* of the survey. Parameters *a* and *b* are user definable weighting factors. The purpose of these factors is to allow some flexibility when the influence of location and size is not the same. For example, if the influence of location is higher than size, a higher value is assigned to *b*, so that the sum of *a* and *b* equals 1.

The *Matching Indices* for considered surveys calculated using equal weighting factors are shown in TABLE VIII.

TABLE VIII
MATCHING INDEX

Survey	1	2	3	4	5
Matching Index	0.95	1.38	0.41	0	1.05

IV. SPRING THEORY

A customized damage function for the assessed plant can be calculated from the Matching Index of each survey utilizing the principles of Hooke's Law of elasticity [16]. In this sense, each survey result (in the form of CDF) is thought to be behaving as a spring pulling the expected output towards it, with *Matching Index* being used as the spring constant that defines its stiffness.

$$\begin{aligned} MI_1 x_1 + MI_2 x_2 &= MI_3 x_3 + MI_4 x_4 \\ x_1 + x_3 &= d_1 \\ x_2 + x_3 &= d_2 \\ x_3 - x_4 &= d_3 \end{aligned} \quad (5)$$

Interaction of several surveys would generate an output when static equilibrium is achieved. This metaphor is pictured in Fig.6, where the position of the block is pulled by four springs (surveys). Equilibrium is achieved when the block is static and its position becomes the final output of the proposed methodology. At equilibrium, the net force on the block is zero and equation (5) applies. Values *d1*, *d2* and *d3* in (5) can be obtained from the CDFs of individual surveys.

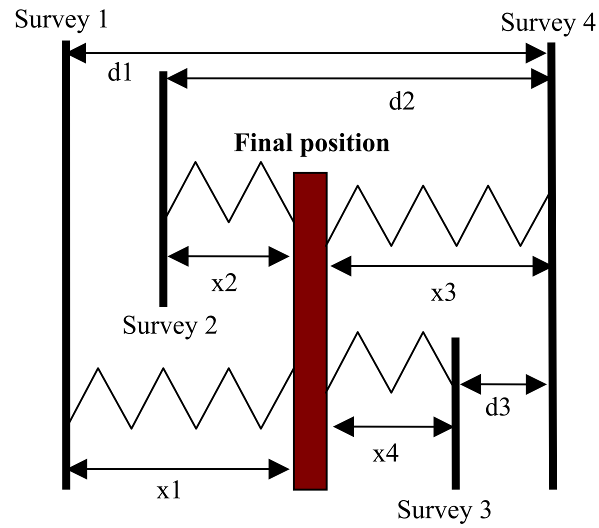

Fig. 6. Final position of the block at equilibrium

Solving (5) for all interruption durations yields the customized CDF of the assessed plant. Fig.7 shows the results of applying the proposed methodology to the case study. The customized damage function is a product of influences from all survey results, with more influence from the survey with higher *Matching Index*.

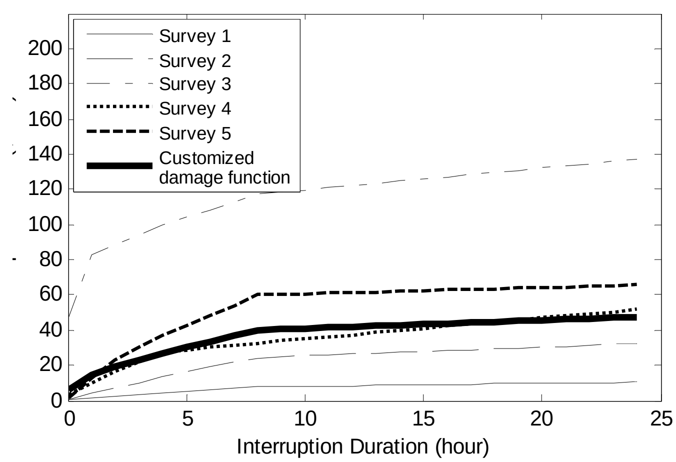

Fig. 7. Customized damage function

V. CONCLUSIONS

A new methodology is proposed to derive customized customer damage function for individual industrial plant based on available data from surveys conducted at similar plants around the world. It considers all known factors that influence costs, including customer process type, size and location, and implements well known Hooke's Law of elasticity to derive the appropriate customized CDF. The methodology is intended to be used by practicing engineers in industrial plants and therefore the paper provided detailed step by step procedure for its proper implementation.

VI. Acknowledgment

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